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Development of Nonwoven Flame Resistant Coverall for Military Applications

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Abstract

The U.S. Army desires low cost combat uniform fabrics that provide flame protection, visual and near infrared camouflage, comfort, and durability. Prior to material development, the flame threat and hazard was investigated and characterized. Flammability related test methods were reviewed and pass/fail criteria for instrumented manikin testing was established based on military medical doctrine. Various fibers, fiber blends, and functional finishes were investigated and novel blend materials were developed. Textile manufacturing methods not traditionally used in military protective clothing such as core-spun yarn spinning and direct fiber-to-fabric non-woven technologies were also investigated. When compared to the standard issue combat uniform, the best performing protective clothing configuration demonstrated a reduction in total body burn from 88 to 8 percent.

Historic Background

Flame and incendiary weapons are the oldest weapons known to man. According to a recent threat assessment conducted by the National Ground Intelligence Center, the use of incendiaries in battle dates back to biblical times. One of the first flame projectors consisted of a hollow tree trunk that had an attached basin full of glowing coals, sulfur and pitch. A bellows blew the flame in the form of a jet, setting fire to enemy fortifications. Other weapons include early firebombs hurled from catapults, incendiary arrows, and a material known as "Greek Fire." Its formula was kept secret and the exact composition was never identified. It would readily ignite other combustible materials and was difficult to extinguish. Flame and incendiary weapons dominated the battlefield for many centuries until the introduction of gunpowder in the fifteenth century. Flame and incendiary weapons have been used in virtually every war since that time, and are used in current conflicts today. Protection from these threats, their secondary hazards, and accidental fires that occur on the battlefield are highly desired by today's military users.

Introduction

U.S. Army tankers and aviators of all services are required to wear flame resistant clothing systems made from Nomex® and Kevlar® fiber blend fabrics. The infantry, which wears a nylon and cotton blend fabric, desires flame protection, but uniforms made from Nomex and Kevlar blend fabrics are too expensive to issue to every soldier. The objective of this effort is to develop new materials and system protection strategies that are affordable and improve the survivability of the individual soldier. Prior to material development, the flame threat and hazard was investigated and characterized. Flammability related test methods were reviewed and pass/fail criteria for manikin testing was established based on military medical doctrine. In addition to low cost flame protection, a fabric is desired that provides the multi-functionality of the all-purpose combat uniform currently in use, i.e. visual and near-infrared camouflage protection, comfort in environmental extremes, and durability and protection against the elements.

Flame and Thermal Threat

The likelihood of the military flame burn hazard on the battlefield can be attributed to three components: threat-generated flame burns, incidental or secondary flame burns, and burn accidents. The threat-generated burn hazard results from the direct employment of a flame and thermal weapon. Incidental or secondary flame burn hazards result from flame and thermal weapons or other threats (i.e. ballistic, blast, chemical, directed energy) igniting battlefield combustibles, including clothing or equipment that can also present a burn hazard, in addition to the direct effect of the specific threat. Accidents comprise the remaining burn hazard and account for over half of all burns. Historically, even in combat, flame burn injuries more often result from the ignition of battlefield combustibles, due to accidents or secondary flame effects in the environment, than from direct flame and thermal threats[1]. The thermal characteristics of many battlefield combustibles were reviewed. According to Kim, the estimated values of the heat flux of thermobaric, incendiary, and flame weapons, and JP-8 fuel converge to a common heat flux of about 2.0 cal/(cm^2 sec) over time[2]. Since the likelihood of survival of a direct hit from a flame and thermal weapon is low based on the initial ignition temperatures and known blast effects, and the fact that most burn injuries result from the secondary effects of the environment, a thermal flux of 2.0 cal/(cm^2 sec) was selected because it is representative of a reasonable military fire hazard that is survivable if exposure time is short. Appropriately developed protective clothing should provide critical seconds of increased escape time to distance oneself from the flame hazard and thereby provide a lesser, survivable exposure time.

Clothing Systems Test and Evaluation

Flammability test methods were reviewed and the instrumented manikin test, ASTM F 1930, which targets a thermal flux of 2.0 cal/(cm^2 sec), was selected for clothing system test and evaluation. The establishment of pass/fail criteria for the test was based on military medical doctrine. A partial listing of the accepted criteria for transferring patients to a burn center include: (a) partial-thickness burns of 20 percent total body surface area burned (TBSAB) or greater in adults, (b) full-thickness burns exceeding 5 percent TBSAB, and (c) burns involving the face, feet, hands, perineum, or major joints. During armed conflict, however, additional criteria include casualties with small burns involving the hand, foot, or perineum that may be considered for early evacuation since their activity will be disproportionately limited[3]. In addition, during combat, available resources must be expended on those individuals with the greatest chance for survival. Casualties at the extremes of age (that is, those under 10 or over 60 years old) or those with 70 percent of the total body surface area burned will, in general, do poorly, and should be allocated a lesser share of the resources. The care of casualties with less than 20 percent TBSAB can safely be delayed pending either their evacuation to a higher-echelon medical treatment facility or the availability of more resources[4,5]. Pass/fail criteria for the instrumented manikin test were established as no more than a 20 percent TBSAB based on the likelihood of the availability of treatment during combat.

Instrumented manikin testing was conducted on both aviator and tanker protective clothing systems beginning with summer weight and adding clothing layers up to the full winter weight configuration (Table 1). The clothing systems were tested from three to ten seconds of exposure (Table 2)[6]. Safe exposure limits were established for each clothing configuration (Table 3). Safe exposure limits were identified based on the protection provided for each system. This approach was selected for two reasons: 1) many military protective clothing systems provide protection against multiple battlefield threats, hazards, and conditions, and the protection mechanisms for each may be mutually exclusive, and 2) the flame and thermal exposure time is random and therefore difficult to specify exposure limits increase with each additional clothing layer. The first line of defense against the flame assault is the outer-layer, which in every configuration is flame and ignition resistant. Each additional clothing under-layer adds insulation and increases protection time. Tests performed with both cotton long underwear and Nomex long underwear show no difference in performance. These findings corroborate other studies[7] demonstrating that the entire clothing system, especially the under-layers, does not necessarily need to be made from flame resistant materials. The aviator and tanker systems performed similarly at various exposures with the exception of the summer weight configuration. The tanker coverall demonstrated a second-degree body burn of 8 percent versus 18 percent for the two-piece aviator system. The differences are likely due to differences in material type and garment construction. The tanker coverall was made from a 4.5 ounce/yard^2 producer colored Nomex fabric, and the aviator coat and trousers were made of a 5.5 ounce/yard^2 camouflage printed Nomex and Kevlar fiber blend.

Table 1. Aviator and Tanker Clothing Configurations

Configuration	A. Aviator	B. Tanker
1	T-shirt[8] and Briefs[9] Aircrew Coat[10] and Trouser[11] Lightweight Balaclava[13] Nomex Gloves[14] Combat Boots [15]	T-shirt and Briefs Combat Vehicle Crewman (CVC) Coverall[12] Lightweight Balaclava Nomex Gloves Combat Boots
2	Cotton Long Underwear Aircrew Coat and Trouser Lightweight Balaclava Nomex Gloves Combat Boots	Cotton Long Underwear Combat Vehicle Crewman Coverall Lightweight Balaclava Nomex Gloves Combat Boots
3	Nomex Long Underwear[16] Aircrew Coat and Trouser Lightweight Balaclava Nomex Glove Combat Boots	Nomex Long Underwear Combat Vehicle Crewman Coverall Lightweight Balaclava Nomex Gloves Combat Boots
4	Nomex Long Underwear Aircrew Coat and Trouser Aircrew Jacket and Liner[17] Lightweight Balaclava Nomex Gloves Combat Boots	Nomex Long Underwear Combat Vehicle Crewman Coverall Combat Vehicle Crewman Jacket[18] Lightweight Balaclava Nomex Gloves Combat Boots
5	Nomex Long Underwear Aircrew Coat and Trouser Bib Overall[19] Aircrew Jacket and Liner Cold Weather Balaclava[20] Nomex Gloves Combat Boots	Nomex Long Underwear Combat Vehicle Crewman Coverall Bib Overall Combat Vehicle Crewman Jacket Cold Weather Balaclava Nomex Gloves Combat Boots

Table 2. Summary of Burn Injury Prediction

	Exposure Time											
	3 seconds			4 seconds			6 seconds			10 seconds		
	% Predicted Burn*			% Predicted Burn*			% Predicted Burn*			% Predicted Burn*		
Ensemble	2^{nd} degree	3^{rd} degree	Total	2^{nd} degree	3^{rd} degree	Total	2^{nd} degree	3^{rd} degree	Total	2^{nd} degree	3^{rd} degree	Total
1A	18	2	20	23	7	30	25[a]	31[a]	56[a]			
2A	0	2	2	2	2	4	17	3	19			
3A	0	2	2	2	2	4	26	2	28			
4A				2	2	4	9	2	11			
5A				0[a]	2[a]	2[a]	0	2	2	1	4	5
1B	8	2	10	13	16	29	22[a]	43[a]	65[a]			
2B	1	2	3	3	3	6	18	14	32			
3B	0	2	2	2	2	4	21	9	30			
4B				2	2	4	8	4	13			
5B				0[a]	2[a]	2[a]	0	2	2	2	3	5

* Average of replicate measurements
[a] Result of one measurement

Table 3. Safe Exposure Limits for Military Flame Resistant Clothing

Configuration	1	2	3	4
Layer				
One	T-shirt, Briefs *Cotton*	Long Underwear *Cotton or Nomex*	Long Underwear *Nomex*	Long Underwear *Nomex*
Two	Coverall or ABDU *Nomex*	Coverall or ABDU *Nomex*	Coverall or ABDU *Nomex*	Coverall or ABDU *Nomex*
Three			Overall *Nomex*	Bib-Overalls *Nomex*
Four				Jacket *Nomex*
% Body Burn	Less than 20% At 3 seconds	Less than 20% At 4 seconds	Less than 20% At 6 seconds	Less than 20% At 10 seconds

Materials Development and Discussion

The overall objective was to develop a low cost flame resistant fabric for use by the infantry that also provides the multi-functionality of the all-purpose combat uniform fabric currently in use, i.e. visual and near-infrared camouflage, comfort in climatic extremes such as hot and humid, and hot and dry, and durability and protection against the elements. As a guide, the military standard camouflage printed Nomex fabric was used for general performance goals. Fibers, fiber blends and functional finishes investigated include: Basofil, FRT cotton, FRT cotton/nylon, FRT Tencel, FRT cotton/Kevlar/nylon, carbonized rayon/Nomex, Kevlar/FR rayon, Nomex/FR rayon, PBI and PBI/FRT cotton. Weight and strength data for these fabrics are listed (Table 4) with those for the military camouflage printed Nomex fabric.

Table 4. Performance Characteristics of Developmental and Commercial Materials

Fiber Blend		Weight, oz/sq.yd	Tearing Strength, lbs.	Breaking Strength, lbs	Flame Resistance
MIL-C-83429 92% Nomex 5% Kevlar 3% P140	Class 5	4.7-6.0	9 x 7 (min.)	180 x 100 (min.)	Yes
	Class 6	4.3-5.0	12 x 8 (min.)	180 x 100 (min.)	Yes
93% Nomex 5% Kevlar 2% P140 (Spun Laced)		3.1	Does not tear	109 x 100	Yes
58% FR Cotton (sheath) 2% Mannacryl (sheath) 40% Kevlar (core)		4.5	8 x 8	107 x 61	Yes
80% FR Cotton 20% PBI		5.0	9 x 7	83 x 48	Yes
58% FR Cotton 27% Kevlar 15% Nylon		6.3	3 x 3	153 x 160	Yes
58% FR Rayon 40% Kevlar 2% Conductive Fiber		6.4	10 x 13	150 x 100	Yes
65% Nomex 35% Rayon		6.5	9 x 6	131 x 102	Yes
80% FR Cotton 20% PBI		6.6	11 x 6	139 x 75	Yes
Carbonized Rayon Nomex		6.9	10 x 8	198 x 125	Yes
100% FR Lyocell (Tencel)		7.4	6 x 7	180 x 117	Yes
88% FR Cotton 12% Nylon		7.7	6 x 7	99 x 72	Yes
88% FR Cotton 12% Nylon		11.0	5 x 9	161 x 154	Yes

Many of the inherently flame resistant fibers were eliminated for use in a homogeneous fabric due to their high cost and the requirement for visual and near infrared camouflage.

The high polymer orientation of the aramids and PBI, for example, contributes to their flame resistance, but also reduces or eliminates their ability to be dyed with traditional dyestuffs due to the lack of chemical dye sites. Some of these materials may achieve coloration by pigment injection in solution form, but their versatility is limited. Aramid blends are dyed and camouflage printed using proprietary technology that adds significantly to the final cost of the finished fabric. Still prized for their inherent flame resistance, some of these fibers were blended with low cost fibers to enhance the overall flame resistance of the fabric. Flame retardant rayon, which is inherently flame resistant rather than flame retardant treated, was blended with the aramids in 60/40 and 35/65 percent blend ratios, but these materials fell short of the desired fabric strength and the camouflage print demonstrated poor colorfastness.

Flame-retardant treated cotton has long been the industry standard for use in low cost flame resistant industrial work wear. However, the most commonly used treatment Indura® adds 20 percent to the weight of the fabric. Flame-retardant treated cotton was blended with nylon in 88/12 percent blend ratios, where the nylon was added to improve strength. While the addition of the nylon did not negatively impact the flame resistance, a heavier weight fabric of 11 ounces/yard^2 was required to achieve relatively acceptable breaking and tearing strengths. Flame-retardant treated cotton was also blended with Kevlar and nylon to enhance flame resistance and improve abrasion resistance in a 58/40/15 percent blend ratio. While the Kevlar was the strongest of the three fibers, it occupied less than 50 percent of the total material composition to keep costs down. The strength of the fabric is dictated by the dominant fiber, which in this case, was the lower strength cotton. In addition, the high end and pick count required to anchor the Kevlar fiber detrimentally reduced the fabric tearing strength to three pounds in the warp and filling directions. PBI was blended with flame-retardant treated cotton in 20/80 percent blend ratio in 5.0 and 6.6 ounce/yard^2 weights, however, the performance characteristics of the predominate fiber, cotton, prevailed.

Basofil fiber demonstrated low fiber tenacity and developmental efforts were directed toward insulation, knitted headwear and hand wear applications where high strength was not a critical factor. Blends of carbonized rayon and Nomex were investigated and while they demonstrated good strength performance they could not be dyed and camouflage printed. Flame-retardant treated Tencel demonstrated good strength but the camouflage demonstrated poor colorfastness performance[21]. Core spun yarns were investigated and developed with the primary intent of manufacturing a yarn with a high strength, inherently flame resistant core, and low cost readily camouflage printable sheath fiber. The best performing material combination was a cotton sheath, Kevlar core yarn. These materials also fell short on strength because only the Kevlar-based core and not the sheath contributed to the fabric strength.

While all of the developmental materials investigated met the fabric bench scale flame performance goals (ASTM D 6413; 2.0 seconds, maximum after flame; 25.0 seconds, maximum after glow; 4.0 inches maximum char length), strength and other performance requirements such as colorfastness of the camouflage fell short. As an alternative, we investigated a novel approach to soldier flame protection and changed the focus of fabric development from flame-retardant treated wovens made from low cost fiber blend yarns to direct fiber to fabric manufacturing potentially saving on yarn spinning, fabric weaving, and finishing. A spun-laced non-woven Nomex and Kevlar blend fabric developed by Dupont demonstrated strength that was equal to or greater than the former all-cotton Hot Weather Battledress Uniform (BDU)[22,23] and half the weight. Due to it's lightweight, open, air permeable construction it can be worn over the existing BDU and together this configuration provides a 40 percent cost savings over the existing camouflage printed Nomex/Kevlar Aircrew BDU used by Army aviators. Instrumented manikin testing (Table 5) demonstrated that when the Nomex coverall (Nomex® Limitedwear) was worn over the standard BDU the total body burn was reduced from 88 to 8 percent. Safe exposure limits up to 5 seconds were established. The non-woven Nomex outer-shell provides ignition resistance, and the under-layers of the BDU, t-shirt and briefs provide thermal insulation.

Table 5. Results of Thermoman Burn Injury Prediction

	3 Seconds			4 Seconds			5 Seconds			6 Seconds		
Ensemble	2^{nd}	3^{rd}	Total	2^{nd}	3^{rd}	Total	2^{nd}	3^{rd}	Total	2^{nd}	3^{rd}	Total
T-shirt, briefs,	9	71	80									
HWBDU	14	74	88									
T-shirt, briefs,	1	6	7	4	7	11	4	11	15	10	14	24
HWBDU,	0	7	7	5	7	12	3	9	12	7	13	20
Limitedwear	1	7	8	3	8	11	7	11	18	8	13	21

Garment Development and Discussion

User field evaluations were conducted with the commercial off the shelf (COTS) coverall with mechanics at Fort Lewis, Washington, and combat arms, at Dahlonega, GA to determine if the coverall could be used "as is." The key findings were that the coverall needed to be designed, sized, and hardened to support military clothing applications. A new prototype was developed with a new sizing system, increased ease, and elasticized waist and seat to better fit the military population. A larger two-way brass zipper, and elasticized wrist and ankles were added to enhance user acceptability. Knee, seat, and elbow patches were added to increase the durability. In addition, pigment printing of the camouflage pattern was investigated, and was determined to better suit the nonwoven fabric construction and its wear life. Thermo-man testing (Table 6) demonstrated that the changes did not negatively impact the flame protection of the prototype coverall.

Table 6. Results of Thermoman Burn Injury Prediction on Military Prototype

Ensemble	3 Seconds 2nd	 3rd	 Total	4 Seconds 2nd	 3rd	 Total
T-shirt, briefs HWBDU	9 14	71 74	80 88			
T-shirt, briefs HWBDU, Military Limited Wear				2 0 1	7 7 7	9 7 8

Conclusions and Recommendations

Flame burn injuries more often result from the ignition of battlefield combustibles than from direct flame and thermal threats. A review of the estimated heat flux of several battlefield combustibles shows that they converge to 2.0 cal/(cm^2 sec) after a few minutes. This thermal flux was selected as representative of a reasonable military fire hazard that is survivable if the exposure is short and protective clothing is worn. Pass/fail criteria for clothing systems flammability testing was selected as no greater than a 20 percent body burn based on military medical doctrine. Material selection and clothing configuration influence system flame protection. The entire configuration does not necessarily need to be flame resistant, however, the outer-most materials are the first line of defense against flame and thermal assault and must be flame resistant. Each additional clothing under-layer adds insulation and increases protection time. Military flame protective clothing systems provide 3 to 10 seconds of protection depending on the number of clothing layers worn. The Air Crew BDU and CVC coveralls provide three seconds of protection. The addition of long underwear (cotton or Nomex) increases protection time to four seconds. The addition of a bib overall and jacket provide 10 seconds of protection. The Infantry, which wears a uniform made from a nylon/cotton blend fabric, desires low cost flame protection. Various fibers, fiber blends, and functional finishes were investigated and novel blend materials were developed. While a direct fabric substitution could not be made a supplemental flame resistant over-garment is recommended. When compared to the standard issue combat uniform, the combination of the HWBDU and Nomex coverall demonstrated a reduction in total body burn from 88 to 8 percent. When redesigned, sized, and hardened to support military applications the coverall showed no change in flame protection.

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